



Power electronic converters for microbial fuel cell energy extraction: Effects of inductance, duty ratio, and switching frequency

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HIGHLIGHTS

- ▶ Examined the effects of switching power converter configuration on MFC performance.
- ▶ Analyzed the effects of inductance, duty ratio, and switching frequency.
- ▶ Demonstrated the cross-link effects on MFC energy harvesting performance.

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ABSTRACT

Power converter based microbial fuel cell (MFC) energy harvesting has been recently researched to replace the external resistors that have been utilized to show MFC output in many studies. The electronic circuit can operate as an equivalent external resistor, but the energy generated from MFC can be harvested in storage instead of being dissipated. However, there is limited information in the literature about the effects of operating configuration of power electronic circuits on MFC energy harvesting. In this study, a boost-converter based energy harvester circuit was examined in terms of inductance, duty ratio, and switching frequency. The results showed that all of these factors play important roles for the performance of MFC and energy harvesting, and their effects can be cross-linked. Current and voltage is generally proportional and inversely proportional to the inductance, respectively. The total harvested energy and efficiency vary significantly by combinations of duty ratio and switching frequency. For the MFC reactor tested in the study, the highest energy harvested was 3.48 J which was under the combination of 14 mH inductance, 75% duty ratio and 5000 Hz frequency, comparing to the highest efficiency of 67.7% happened at 130 mH inductance, 25% duty ratio and 4000 Hz frequency. When using the smallest inductance of 0.45 mH, the highest energy and efficiency were only 1.38 J (50% duty ratio and 5000 Hz frequency) and 19.9% (25% duty ratio and 5000 Hz frequency), respectively. Regardless of the voltages and currents produced in various operating configurations, anode potentials were stable, suggesting that there were enough electrons available to be utilized for current generation. An optimal operating configuration that provides ideal system performance can be found for different reactors and applications.

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1. Introduction

Microbial fuel cells (MFCs) are considered new green energy sources due to their wastewater treatment and simultaneous energy producing capability. In most studies so far, an external resistor was inserted between the anode and cathode of an MFC, so the voltage across the resistor can be monitored to demonstrate the power

production. However, this method does not harvest any energy because the energy is dissipated on the resistor as heat. Furthermore, the relatively low voltage (<1.0 V) and low power ($\sim \text{W/m}^3$) output from an MFC cannot directly support majority of commercial electrical devices, which is one of the biggest obstacles for practical application of MFC. Recently power electronics based harvester circuits for MFCs have been researched [1–5], aiming significantly improved MFC energy harvest and output voltage boost, which can be a crucial step to make MFC technology commercially viable. Different from conventional operations using external resistors, energy generated from MFCs will be collected and stored, which in

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turn will be utilized to power electrical devices, for example, wireless sensors to monitor environment [6,7].

To design boost-converter based circuits for more versatile and efficient MFC energy harvesting, there are three fundamental factors to consider: the inductance of an inductor, extraction duty ratio (also known as duty cycle), and extraction frequency (i.e. converter switching frequency). The inductor is the intermediate energy storage for an MFC and determines the rate of current change and level of energy extraction. Large inductance makes the current changing slowly while small inductance makes it faster, and this contributes to determine the MFC terminal voltage. The duty ratio governs the relative duration of energy extraction in a certain switching period. In other words, it determines the time period of energy extraction and MFC recovery. In MFC recovery period, the energy harnessed in inductor is transferred to the capacitor storage. Higher duty ratios lead to longer energy extraction and shorter time for MFC recovery, while low duty ratios allow more time for MFC to recover and energy transfer. The switching frequency determines the number of energy extraction and transfer within a given time period. Higher switching frequency means the energy extraction happens more frequently, but each extraction is shorter for a given duty ratio. The total energy extraction time is determined by duty ratio regardless of switching frequency, which can be given as $T_{\text{ext}} = D \times T_{\text{prd}}$. For example, the energy extraction with 50% duty ratio at 1000 Hz switching frequency has the same energy extraction time of 500 msec per 1 s period as the 50% duty ratio at 2000 Hz frequency, but the number of energy extraction cycle for the first case is 500 times, only half of the latter case. However, it has been revealed that different combinations of duty ratio and switching frequency affect MFC energy harvesting results, even if the energy is harnessed for the same amount of time.

There are very few studies that investigated how to capture MFC energy more effectively through the design and optimization of electronic harvesting circuits, especially by using high-speed switching converters. Dewan et al. [8] concluded that intermittent energy harvesting (IEH) by alternatively collecting energy in the capacitor and dispensing it through a resistor was more

effective than continuous energy harvesting (CEH) with constant energy extraction. The capacitor was charged for hours but discharged for only less than a minute, which indicated that electro-active species around the electrode was replenished while the capacitor was being discharged. Gardel et al. [9] obtained similar results with duty cycling based energy harvesting from a multi-anode MFC, which suggests that it was necessary to replenish depleted electron donors within the biofilm and surrounding diffusion layer to maximum charge transfer. Grondin et al. [10] also investigated the power output as a function of duty cycle, but the effect of extraction frequency was not studied.

We recently developed a boost-converter based energy harvesting circuit for MFCs [11], and our results showed that the new active harvesting approach was much more efficient than passive charge pump method, as the energy output increased by 76 times [11]. In the active harvesting circuit, energy extraction was controlled within a voltage band at the MFC's maximum power points. The selection of inductance was based on a fixed condition of the MFC, but the duty ratio and switching frequency were flexibly controlled based on MFC condition [11]. In this study, we investigated the energy extraction with different inductances, duty ratios, and switching frequencies to characterize how these parameters affect MFC energy output performance. The energy harvesting frequency or switching frequency of the power converter ranges from 100 to 5000 Hz, which means that our switching periods (10 msec–200 μ sec) were orders of magnitude shorter than previous studies, which were in the range of hours [8], minutes [12] and seconds [9,10].

2. Materials and methods

2.1. MFC construction and operation

As shown in Fig. 1, a two-chamber MFC reactor with anode and cathode chamber separated by cation exchange membrane (38 cm², CMI-7000, Membranes International) was used in this study [11]. The reactor was originally inoculated by anaerobic

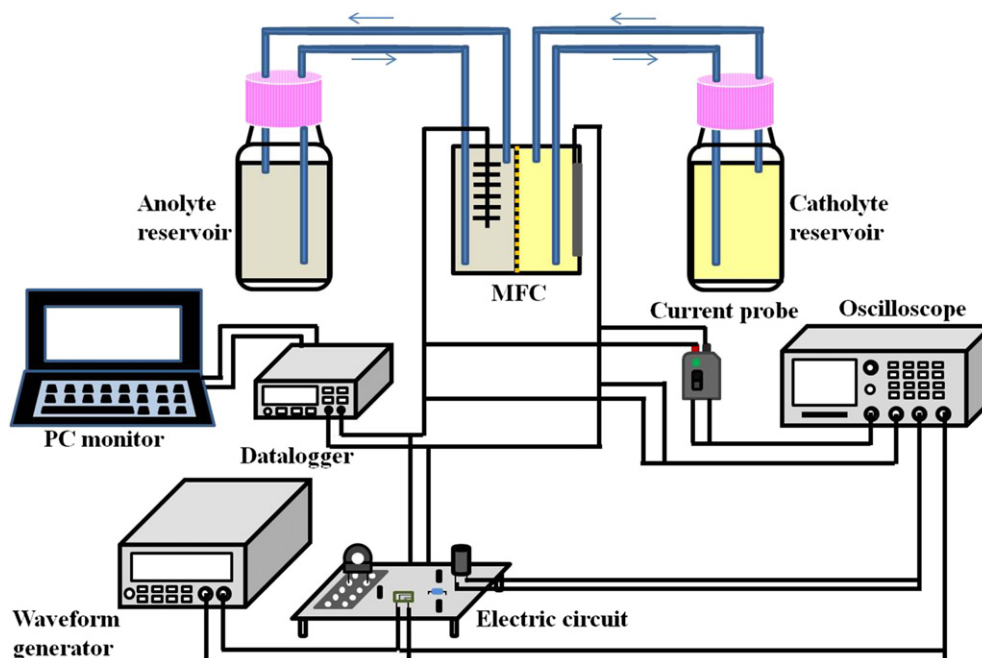


Fig. 1. Schematic diagram of the experimental setup.

sludge from Longmont Wastewater treatment Plant (Longmont, CO) and has been operated stably for nearly one year. The empty volume of anode or cathode chamber each was 150 mL. Anode was a treated graphite fiber brush (Gordon Brush) and cathode was a 38 cm² plain carbon cloth (Fuel Cell Earth). To maintain stable conditions of both anode and cathode during tests, anolyte and catholyte was separately recirculated from a 1000 mL reservoir. The flow rates of recirculation were 45 mL min⁻¹ and 114 mL min⁻¹ for anolyte and catholyte, respectively. The anolyte was sodium acetate dissolved in 50 mM phosphate buffer containing 1.25 g of CH₃COONa, 0.31 g of NH₄Cl, 0.13 g of KCl, 3.32 g of NaH₂PO₄·2H₂O, 10.32 g of Na₂HPO₄·12H₂O, 12.5 mL of mineral solution, and 5 mL of vitamin solution [13]. The catholyte was potassium ferricyanide dissolved in 50 mM phosphate buffer contains 16.5 g of C₆FeK₃N₆, 3.32 g of NaH₂PO₄·2H₂O and 10.32 g of Na₂HPO₄·12H₂O. All of the tests were conducted at room temperature.

2.2. Energy extraction circuit design

Energy extraction circuit based on boost-converter was composed of a metal–oxide–semiconductor field-effect transistor (MOSFET, Si3460BDV, VISHAY), an inductor (Triad Magnetics), an Schottky diode (1N5711, Micro Commercial Components) and a 2 F supercapacitor (PAS1016LR2R3205, Taiyo Yuden). The MOSFET is the main switch of the circuit and controlled by a 15 MHz function/arbitrary waveform generator (33120A, Agilent Technologies). The function/arbitrary waveform generator can generate square waves in various duty ratios and frequencies that turn MOSFET on and off to extract energy from MFC in different conditions. The inductor is a temporary energy storage while the MOSFET is on, and the stored energy is transferred to capacitor when the MOSFET is off. The Schottky diode blocks reverse power flow from capacitor to inductor and automatically turns on when the MOSFET is off due to the induced voltage across the inductor. The capacitor is the terminal energy storage in this study.

Fig. 2(a) shows block diagram of the energy extraction circuit controlled by the function generator. The circuit was operated under two modes: CHARGE (Fig. 2(b)) and DISCHARGE (Fig. 2(c)). Under CHARGE mode, MOSFET is on and switching diode is off, energy harvested from MFC is stored temporarily in the inductor; Under DISCHARGE mode, MOSFET is off and switching diode is on, energy stored in the inductor is transferred to the capacitor. After alternative operation under CHARGE and DISCHARGE modes, energy can be cumulated in the capacitor. Detailed operation of the energy harvester can be found in authors' previous work [5,11].

2.3. Tests

In this study, three different inductors (RC-7 (0.45 mH), CST206-1A (14 mH), and CST206-3A (130 mH), Triad Magnetics), three duty ratios (25%, 50% and 75%) and seven switching frequencies (100 Hz, 500 Hz, 1000 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 5000 Hz) were examined. In each set of the tests, switching frequency was changed with one fixed inductor and duty ratio. So there were total nine sets and each set includes seven tests. Each test lasts for 30 min to examine one specific configuration of inductor, duty ratio and switching frequency. Before each test batch, MFC reactor was fed with new anolyte and catholyte and operated under a 23 Ω resistor to facilitate the recovery of electrochemical active bacteria. A 23 Ω resistor was used because it is correlated to the highest power density based on the system's polarization curve. If MFC reactor output voltage was stable at 355 ± 5 mV with 23 Ω , meaning the MFC was maintained at the maximum power point, the reactor was assumed to be ready for the test. For each test in a different condition, the reactor was initially kept at open circuit

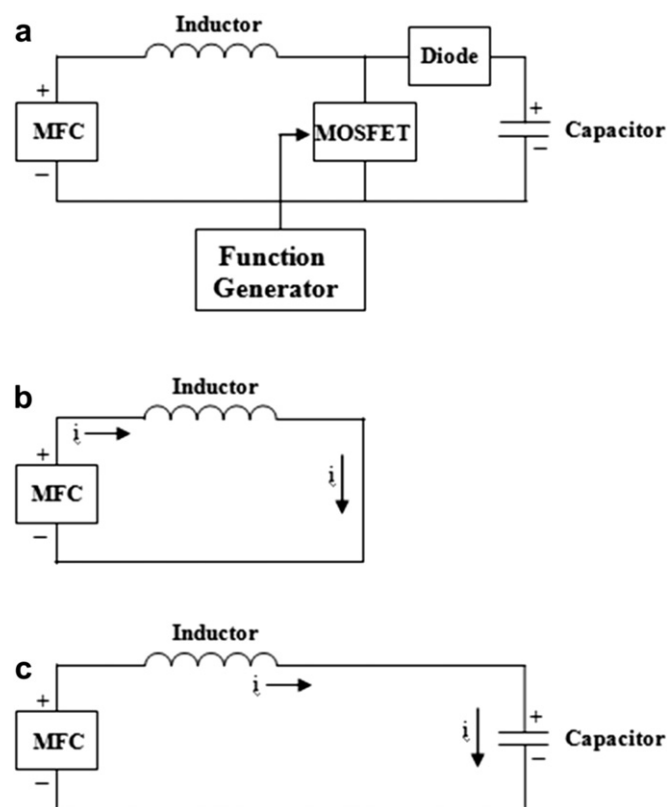


Fig. 2. Block diagram of energy extraction circuit: (a) Energy harvesting converter, MOSFET is controlled ON/OFF in different duty ratios and frequencies by function generator; (b) CHARGE mode, MOSFET is on and switching diode is off, energy extracted from MFC is stored in the inductor temporarily; (c) DISCHARGE mode, MOSFET is off and switching diode is on, energy stored in the inductor is transferred to the capacitor.

condition until it reached an open circuit voltage of 705 ± 5 mV. Then the characterization was conducted from this open circuit condition.

The MFC voltage, anode potential, cathode potential, capacitor voltage, and voltage across the current probe were recorded every 66 s by data acquisition system (Model 2700, Keithley Instrument). Anode potential and cathode potential were measured against an Ag/AgCl reference electrode (RE-5B, Bioanalysis) inserted in anode chamber and cathode chamber, respectively. A digital storage oscilloscope (Tektronix TPS2014) was used to continuously monitor MFC voltage, output current and duty ratio.

The energy stored in the storage capacitor (E) was calculated by $E = 0.5 \int CV^2 dt$, where C is the capacitance, and V is storage capacitor voltage. Energy supplied by the MFC during harvesting (W) was expressed as $W = \int V_{MFC} I_{MFC} dt$, where V_{MFC} is the voltage across the MFC anode and cathode, I_{MFC} is the MFC output current and the sampling time dt is 66 s. Energy harvesting efficiency (EHE) was calculated by $EHE = E/W \times 100\%$. Duty ratio (D) was defined as $D = t_{on}/(t_{on} + t_{off})$, where t_{on} and t_{off} is the on and off time of the MOSFET, respectively [11]. Arithmetic mean values of MFC voltage, MFC current, anode potential, and cathode potential are computed for each 30-min test.

3. Results and discussion

3.1. Effects on MFC voltage and current

The MFC voltages showed the same trend with different inductances, duty ratios and frequencies (Fig. 3(a)–(c)). MFC voltages

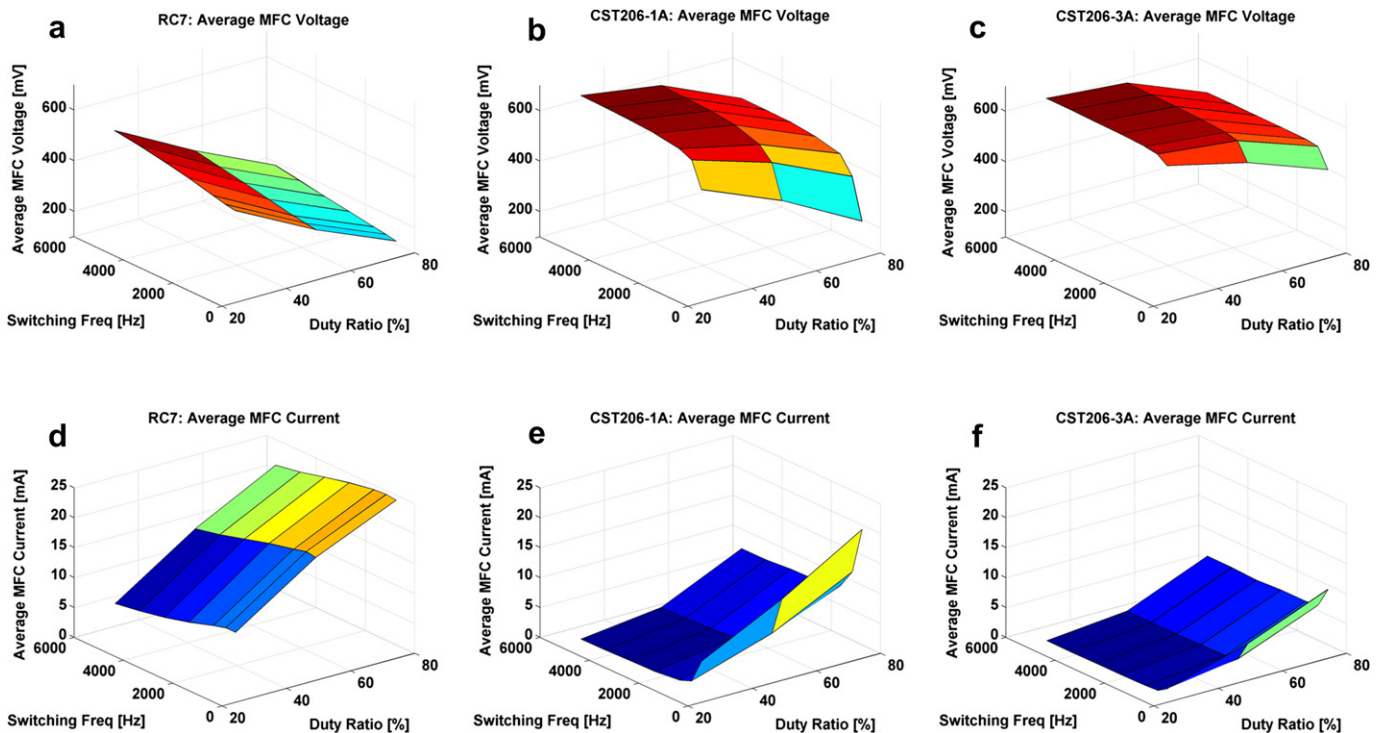


Fig. 3. MFC voltages (a)–(c) and MFC current (d)–(f) during energy extraction under different inductances, duty ratios and frequencies. Left column: 0.45 mH, middle column: 14 mH, and right column: 130 mH.

decreased with increasing duty ratios and decreasing frequencies. Higher duty ratios and low frequencies mean that more time was used for energy extraction from the MFC, so MFC voltage decreases from open circuit voltage in response to the energy extraction. Comparing different inductances, small inductances led to lower MFC voltages than larger inductances, because the smaller inductance will introduce larger current. The two larger inductances (14 mH and 130 mH) showed similar MFC voltages especially with high switching frequencies because of the similar current amplitudes. The current does not show much difference between 14 mH and 130 mH when its amplitude is very low.

The relationship between MFC output current and the inductor can be given as $I_{MFC} = (1/L) \int V_{MFC} dt$ where L is the inductance, V_{MFC} is the MFC voltage, and dt is sampling time. As shown in Fig. 2(b), the voltage across the inductor V_L is identical with MFC output voltage when the MOSFET is on in CHARGE mode. Hence, average MFC output current is inversely proportional to the inductance for a given MFC voltage output, which can be seen in Fig. 3(a)–(f). Although smaller inductance extracts more current, the corresponding voltage is low therefore resulting in low power output.

The rate of current change also depends on the inductance. As can be seen in the voltage and current relationship in the differential form, $V_{MFC} = L(dI_{MFC}/dt)$, the current is increasing fast if the inductance is small for a given voltage. This causes a fast decrease of MFC voltage as well in DISCHARGE period, which generates fluctuations in MFC output voltage, current, and power in the given switching frequency. On the contrary, larger inductance will make them less fluctuating and closer to a constant value due to smaller dI/dt . Typical instantaneous MFC current and voltage waveforms of small and large inductance are shown in Fig. 5(a) and (b). It can be seen that the voltage and current are smoothed and the current level is low with the high inductance.

The MFC voltage and current are also a function of duty ratio. As the duty ratio represents the conduction time of MOSFET, which is the time duration for MFC output terminals connected to the

inductor, the average current increases and voltage decreases with increasing duty ratio. Under a low duty ratio, ON time is short and fewer electrons are extracted, so the produced current is low although there is a long OFF time to replenish electron donors; if ON time is long and more electrons are extracted with a high duty ratio, so the produced current becomes high but the short OFF time may reduce time for electron donor replenishment. Hence, there should be an optimum duty ratio to balance ON and OFF time for a given MFC condition. The experiment with lower inductance case shows more linear relationship between voltage and current in terms of duty ratio. The generated energy surface in low inductance experiment shows clear peak point similar to the polarization curve as can be seen in Fig. 4(a). For higher inductances, the current and voltage do not change as much (Fig. 3(a)–(f)).

The switching frequency also affects the MFC voltage and current. Similar as the duty ratio, it has higher effects when inductance is smaller. For a given duty ratio, MFC generates more current with lower switching frequency because more electrons were extracted at low switching frequency and the reactor can have more time for recovery. This should be very important factor for switching converter based energy harvesting system designs, because MFC voltage may collapse without proper amount of recovery time. However, due to the high switching frequencies (100 Hz–5000 Hz) used in this study, the cycle times were very short ranging from 200 μ sec to 10 msec. Therefore, when energy was extracted within this short period, there were enough electrons available around the electrode for next extraction because only a small portion of the electrons was pulled out. At each duty ratio, current decreased as switching frequency increased because fewer electrons were extracted due to short energy extraction time. The MFC current and voltage showed a tendency to be stabilized after a certain switching frequency (Fig. 3(a)–(f)). In the experiments in this paper, recirculation of anolyte helped improve the mass diffusion and replenish electrons at the electrode.

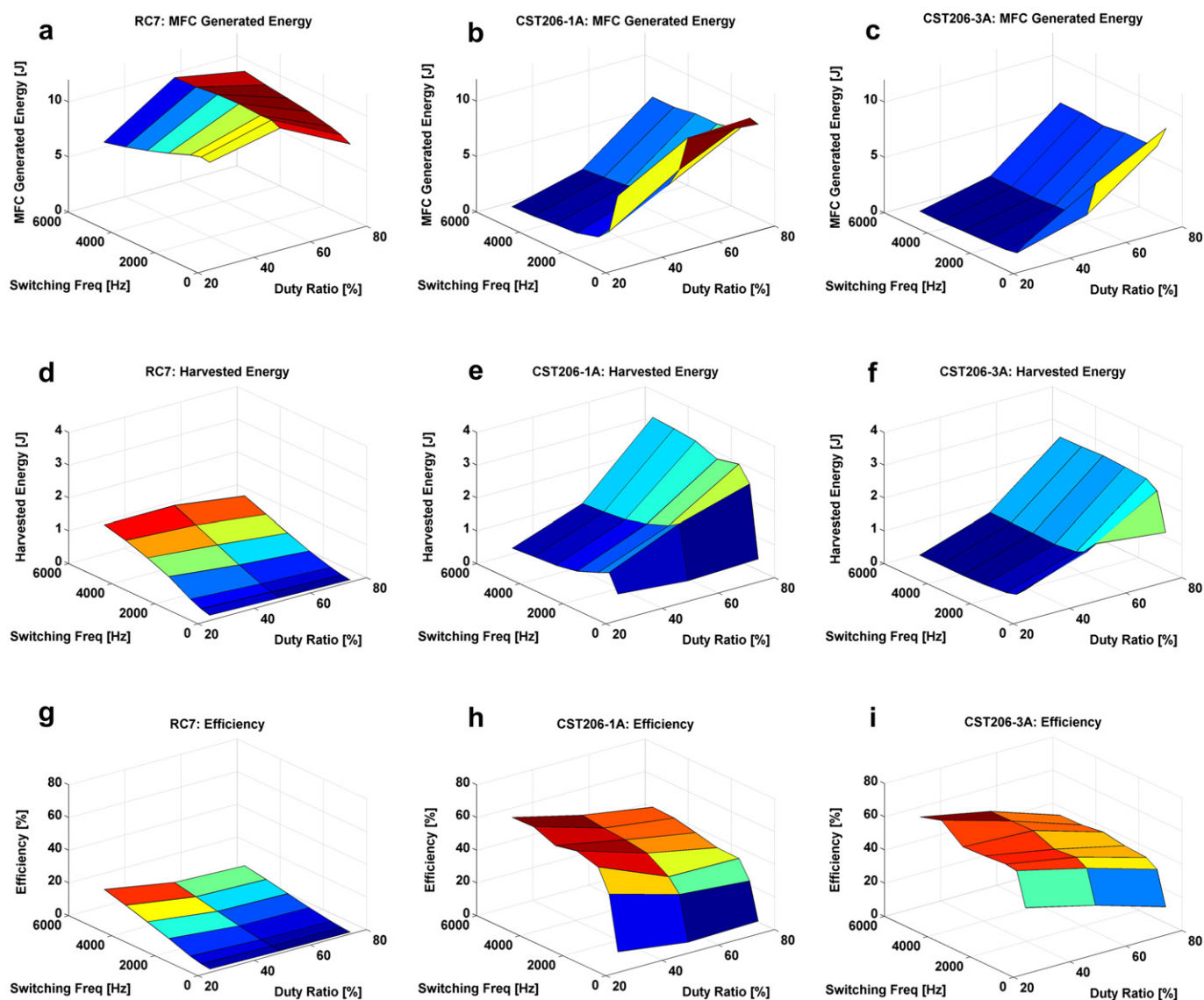


Fig. 4. MFC generated energy (a)–(c), harvested energy (d)–(f), and efficiencies (g)–(i) during energy extraction under different inductances, duty ratios and frequencies. Left column: 0.45 mH, middle column: 14 mH, and right column: 130 mH.

As can be seen in Figure S1 (a)–(f), cathode potentials showed a significant differences for a given duty ratio and switching frequency between low (0.5 mH) and high inductances (14 mH and 130 mH) even with enough catholyte provided during the tests, compared to the anode potentials that were relatively stable. This result suggested that the different duty ratios and frequencies in energy harvesting would not affect the activity of mature anode biofilm (developed on the anode for nearly one year). This confirms that the duty cycling itself had little or no effect on gross community composition on the anode [9]. The stable anode potential also suggested that enough electrons which could be stored in the haem groups of exocyttoplasmic cytochromes [14] were available to be utilized for current generation. If there are not enough electrons produced from bacteria, the problem of overshoot would happen which will reduce cause voltage drop [15].

3.2. Effects on MFC energy and efficiency

The energy that can be stored in the inductor, E_L , can be given as $E_L = (0.5)LI_L^2$, where I_L is the average inductor current. Neglecting

small resistance in inductor and assuming long enough time for discharge, this energy can represent the generated energy from MFC. For a given inductance, the generated power and energy are dominated by duty ratio changes (Fig. 4(a)–(c)), because the duty ratio mainly determines the MFC current and voltage. In the experiment with low inductance (0.5 mH), the generated energy surface shows maximum energy generation points for each switching frequency set because the low inductance allows the MFC generates high enough current to show the polarized characteristics with the given duty ratios (Fig. 4(a)). With other high inductances, the reactor was not able to generated maximum power available even with a high duty ratio. Therefore it can be suggested that the inductance should be carefully selected if the maximum power point operation is required.

The energy harvesting efficiencies can reach up to 60% (Fig. 4(h) and (i)) with large inductances. These were much higher than those with small inductance which was under 20% (Fig. 4(g)). Although MFC reactor can generate more energy under small inductance than large inductances (Fig. 4(a)–(c)), only a small portion of the energy was harnessed because of the low MFC voltage. This is due

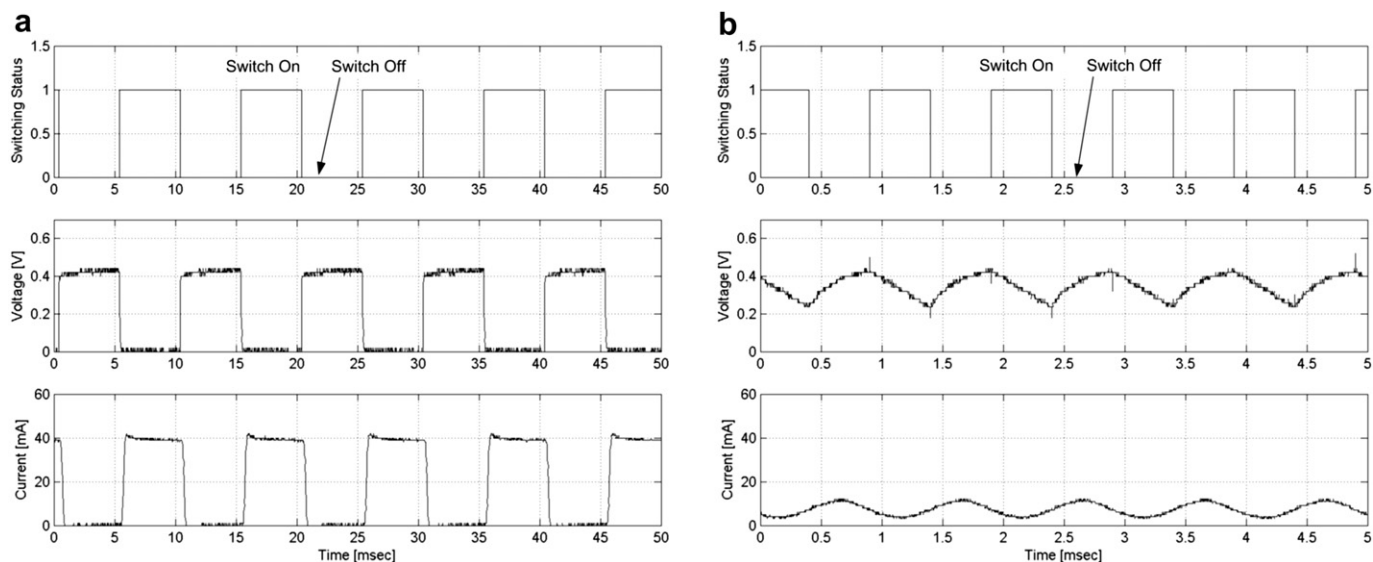


Fig. 5. Waveforms of MOSFET gating signal (top), MFC voltage (middle), and MFC current (bottom). MOSFET is turned on when the gating signal is in high state. (a) Inductance 0.45 mH, switching frequency 100 Hz, duty ratio 50%; (b) Inductance 14 mH, switching frequency 500 Hz, duty ratio 50%.

to the relatively high voltage drop in the harvesting circuit compared to the low input voltage level. Similarly, efficiency is high when duty ratio is low and switching frequency is high (Fig. 4(h) and (i)), but energy output is low (Fig. 4(e) and (f)). The two larger inductances had the similar results on MFC generated energy because they had the comparable current and voltage.

The same trend was achieved by all of the three inductances: the highest efficiency had been reached at the lowest duty ratio and the highest frequency. However, this operating point may not be desirable because the power level is quite low due to the low current. As can be seen in Fig. 4, the harvested energy increases as duty ratio increases, but the efficiency decreases slightly. Therefore an optimal combination of the duty ratio and switching frequency for a given inductance can be found for certain operating conditions, such as maximum power or maximum current operation.

3.3. Discussion

This energy harvesting circuit can be seen as a variable resistance box as a function of inductance, duty ratio and frequency which can operate MFC at different conditions. Although energy harvesting circuit works as a resistor, it is utterly different for its controllability and energy harvesting capability. Resistors only show the energy output potential but cannot harness any usable energy. Energy harvesting circuit can control a specific bio-electrochemical system (BES) as needed and meanwhile energy can be harvested and stored for different uses. For example, for microbial electrolysis cell (MEC) or microbial desalination cell (MDC) reactors, higher current can increase hydrogen production rate [16] or desalination rate [17], so low inductance, large duty ratio and low frequency should be considered. If running a microbial fuel cell (MFC) reactor chasing the maximum power output, medium inductance, medium duty ratio and medium frequency would be a better choice. However, high energy extraction efficiencies were obtained under the large inductance. In our previous work [11], when using maximum power points circuit (MPPC) to extract energy from MFC, the three parameters were 14 mH in inductance, 77.5% in duty ratio and 5500 Hz in frequency. At this combination, the harvested energy was 214 J and the efficiency was only 36% within 18 h, which was much lower than the highest

efficiency (67.7%) achieved in this study. The future work could adjust the three interdependent parameters to extract energy at the maximum power points to obtain higher energy and extraction efficiency. It would be necessary to balance among inductance, duty ratio and frequency to find out the most suitable operation parameters for a specific BES.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jpowsour.2012.07.092>.

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